*
* *

Measuring the Important Characteristics of Acoustic Delay Lines using the UNI-PULSE

*
* *

W M A andersen co., inc.
Pleasant Valley, Conn.
Tel: Area Code 203
FR9-3363

W M A andersen UNI-PULSE

Reference to the block diagram will explain in detail the operation of this instrument.

The stable oscillator covers a frequency range in excess of 1 octave - from slightly below 500 KC to slightly above 1 MC. In normal use, Switch S1 feeds the output of the stable oscillator to a wave shaping circuit. The output of this wave shaper is always available at the frequency of the stable oscillator and the external trigger, at a BNC connector at the rear of the UNI-PULSE chassis. The purpose of this output is covered in the application notes following.

In addition, the wave shaper feeds a chain of 13 Binaries so that delays of less than 1 microsecond to approximately 18,000 microseconds (corresponding to a p.r.f. of 1 MC to 60 CPS) can be generated.

Switch 2 feeds to a pulse shaper so that the appropriate output p.r.f. can be selected.

When Switch S3 is in the "A" position, square wave outputs are available at the BNC connector marked "square wave". In position "B" a positive going video pulse is available, whose width can be varied by the width control knob from 0.2 microseconds to 50% of the duty cycle. In position "C" a negative going video pulse of the same characterization is generated as well as a pulsed r.f. output covering the frequency range of 8.3 to 130 MC.

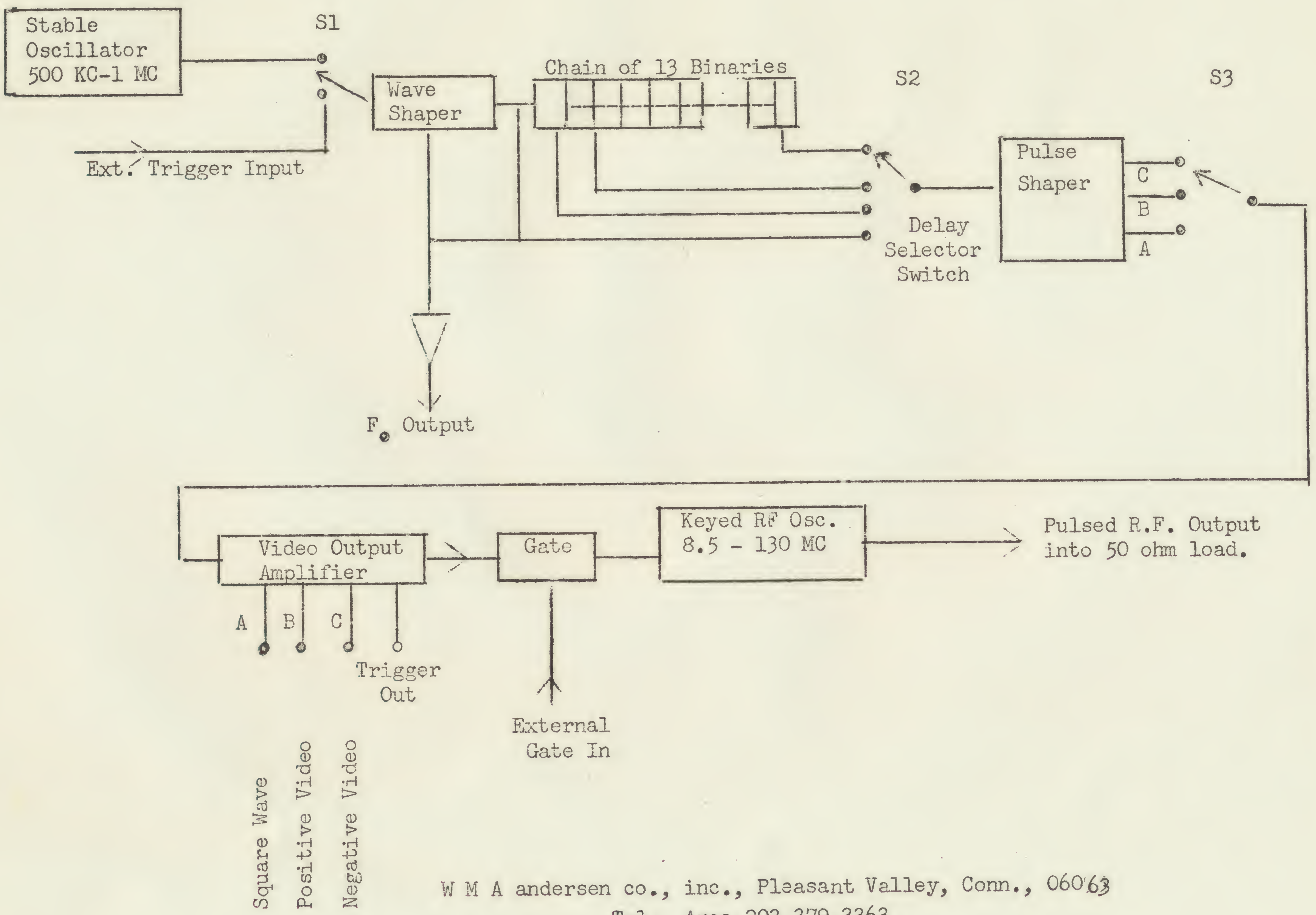
The video output amplifier also keys the pulsed r.f. output circuit when Switch S3 is set to deliver a negative going video pulse.

A gating circuit is provided before the keyed r.f. pulsed oscillator. If a positive going gating signal of 10-25 volts is fed into the appropriate BNC connector at the rear of the chassis, the pulsed r.f. output will be interrupted for the duration of the gate.

This gating circuit is extremely important in certain delay measuring procedures as described in the accompanying paper by McSkimin of the Bell Telephone Labs.

* * * * * * * *

BLOCK DIAGRAM W M A andersen UNI-PULSE



W M A andersen co., inc., Pleasant Valley, Conn., 06063
Tel: Area 203-379-3363

MEASURING THE IMPORTANT CHARACTERISTICS OF ACOUSTIC DELAY LINES USING THE UNI-PULSE

The most important parameters of an acoustic delay line that need to be measured are:

1. Attenuation
2. Bandwidth
3. Spurious signal level
4. Time delay
5. Dispersion of time delay with frequency.

The UNI-PULSE has been designed to generate all signals necessary to make the above measurements. Certain auxiliary equipment will be needed, and this is specifically indicated in the applications as outlined below:

A. MEASUREMENT OF ATTENUATION, SPURIOUS SIGNAL LEVEL & BANDWIDTH OF ACOUSTIC DELAY LINES.

In the following step by step procedure, refer to Fig. 1 below:

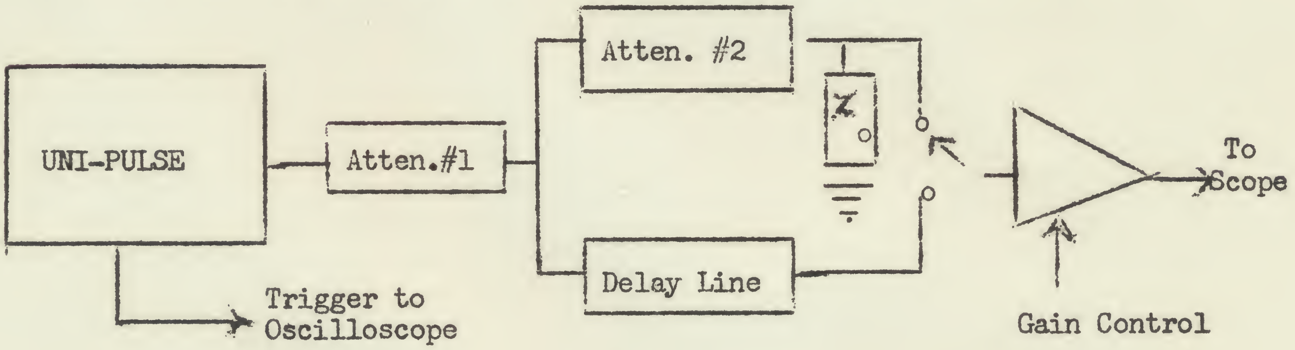


Fig. 1

In Fig. 1 above, it will be noted that there are two attenuators. These should be switch-type attenuators and we would suggest that a 50 ohm impedance level be chosen. The second attenuator is terminated in its characteristic impedance as indicated. The recovery amplifier which drives the oscilloscope should probably be a vacuum tube type designed to have extremely rapid recovery time if it is overdriven.

It may or may not utilize a detector depending on the type of oscilloscope used.

STEP #1 - To measure attenuation switch the amplifier input to the delay line output, and adjust attenuator #1 so that the output amplifier does not saturate when its gain control has been adjusted to some nominal level. The delay range of the UNI-PULSE should be set at 4 to 5 times the nominal delay of the delay line under test, and a relatively wide pulse-width should be used.

STEP #2. After observing the level of the delayed signal on the oscilloscope, switch the input on the amplifier to the output of attenuator #2 - add or subtract attenuation in this attenuator until a signal equal in level to that coming out of the delay line is seen. The attenuation in attenuator #2 will correspond to the attenuation of the delay line.

By repeating the above measurement procedure at 1/2 or at 1 mc increments over the frequency range of interest, the passband characteristics of the delay line can be ascertained. If the gain of the amplifier is increased sufficiently, it will be possible to see spurious signals both before and after the desired delayed signal from the delay line. Usually, it is of interest to know the level of the largest of any such spurious signals. To do this, simply increase the attenuation of attenuator #1 until the amplitude of the main delayed signal is equal to the largest spurious signal of interest. This increase in attenuation will correspond to the spurious level of the delay line. It may be necessary to make this measurement only at the center frequency of the delay line or it may be necessary to perform this measurement several times over some necessary bandwidth.

B. MEASUREMENTS OF DELAY OF ACOUSTIC DELAY LINES.

The standard method of making precise time delay measurements of acoustic delay lines is to adjust the prf of the pulse generating equipment so that it is the reciprocal of the time delay of the delay line.

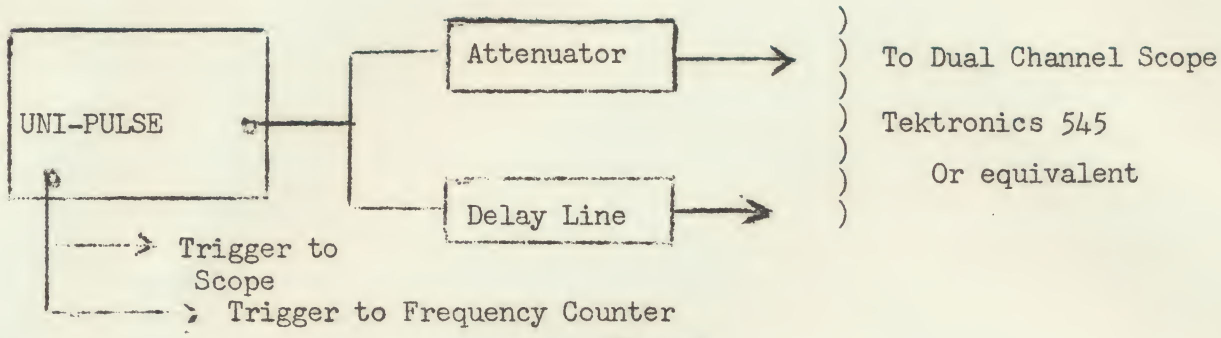


Fig. 2

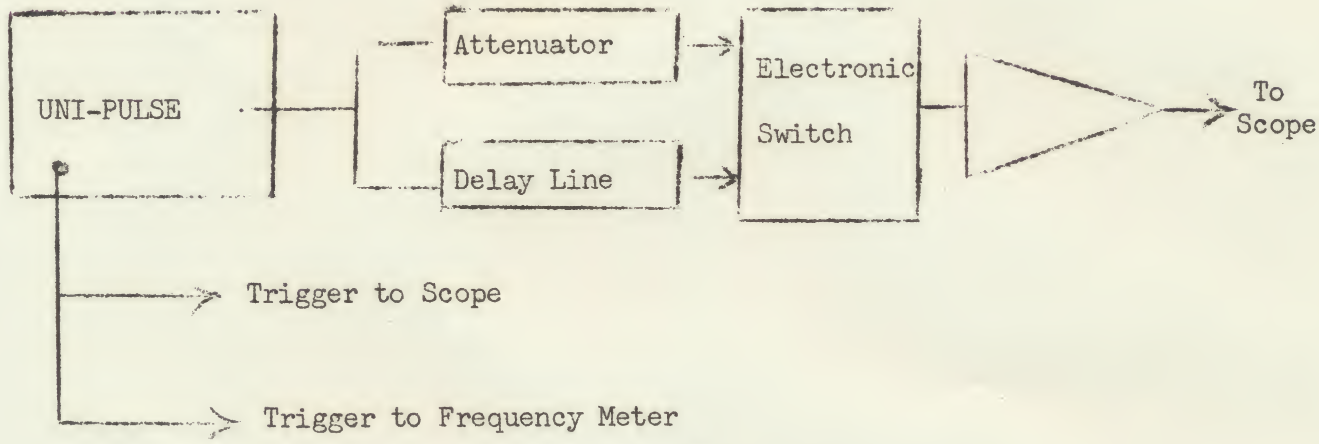


Fig. 3

When viewed on an oscilloscope having two channels or as shown in Fig. 3, on a single channel oscilloscope, the delayed and the undelayed signals will be superimposed. If the setup shown in Fig. 3 is used, either a detected or undetected signal will be fed to the oscilloscope. The primary difference between the two test setups is in the use of a post delay amplifier, which may be necessary if delay lines having an extremely high attenuation are being measured or if the sensitivity of the oscilloscope is too low. With the availability of better scopes today, and with requirements for more precise delay measurements, the setup shown in Fig. 2 is most commonly used and the rf burst is superimposed cycle per cycle. Let us note here, however, that if there is a polarity reversal in the output transducer, the output phase of the delayed signal will be reversed when compared with the undelayed signal, and where extremely tight tolerances of delay is necessary, it is

mandatory that the output transducer be properly polarized.

The setup of Fig. 2 is, we believe, self-explanatory. The frequency counter can be set to measure elapsed time directly or to measure the prf of the trigger. If the frequency counter measurement is made on an elapsed time basis, the accuracy in measurement will be .1 microseconds or .01 microseconds, depending on whether or not the measurement is made over a single period or over 10 periods. This assumes that a 10 mc counter is used. For short delay lines greater accuracy will result if the frequency counter measures the frequency of the prf over a one second or over a ten second increment of time.

As an example, a 100 microseconds delay line measured on elapsed time basis will be measured accurately to either .1% or .01% depending on whether the measurement is made over a time of 1 period or 10 periods. On the other hand, if the frequency of the prf is measured, the accuracy will be .01% to .001% which, in the last instance, will amount to an accuracy of one nanosecond. It is not uncommon today to require even greater precision, and in many instances UNI-PULSE is uniquely able to make this possible providing all auxiliary equipment is of high enough quality.

It will be noted that the delay ranges provided by the selector switch are 1-2 microseconds, 2-4 microseconds, 4-8 microseconds, ..., 8192-16384 microseconds. Obviously, in all of these ranges, the first number corresponds to 2^0, 2^1, 2^2, ..., 2^{13}. The prf of the stable oscillator covers the range of 1 mc down to 500 kc, and the reciprocal of these frequencies corresponds to 1 to 2 microseconds. When the selector switch is set at the range of 1 to 2 microseconds, we are dividing by 1 or 2^0. At any other position, we are dividing by a number corresponding to the first number of the selected range.

Now, since frequency counters always have the ambiquity of ± 1 count, it is possible to greatly enhance the precision of our measurement by measuring the exact frequency of the stable oscillator while at the same time the prf to the delay line is the appropriate prf to satisfy the condition enumerated at the

beginning of this section. For this reason, there is available at the back of the UNI-PULSE an output trigger, which always functions at the setting of the stable oscillator regardless of which range in time delay the instrument is being used at. Considering again a 100 microsecond delay line, Step #1 would be to set the range switch at the 64/128 microsecond range. N, the amount that the stable oscillator frequency is being divided by, is, of course, 64. And $D=\frac{N}{F_0}$ where D is the time delay of the delay line and N corresponds to the number we are dividing by and the F_0 corresponds to the actual frequency of the stable oscillator. If the delay line is exactly 100 microseconds long, F_0 will be 640 kc. Since the error in measuring F_0 will be + or - 1 count, it is obvious that ΔD will equal $\mp \frac{N}{F_0^2}$ which will correspond to an error of approximately .16 nanoseconds. On a shorter delay line an even greater accuracy is inherently available. Where extremely precise delay measurements are necessary, it will be found that analysis should be made of the inherent accuracy possible depending on the range of delay to be measured.

It will be noted that on the front panel of the UNI-PULSE there is a knob labeled "Rise Time". This control will degrade the rise time of the pulsed rf signal. To those familiar with the process of making precise delay measurements of acoustic delay lines, it is known that if the rise time of the pulse driving the delay line is too fast, it will be impossible to adjust the prf for exact superposition of the delayed and undelayed pulses, since the rise time through the delay line may be greatly degraded. This is cause by two things:

1. Insufficient bandwidth in the delay line,
2. Velocity dispersion with frequency.

By adjusting the rise time control, it will become possible to get an almost identical rise time in both the delayed and undelayed channels. Obviously it is desirable to work with as fast a rise time as possible, and we would suggest that initially a very fast rise time be used and the amplitude levels of the delayed and undelayed pulses adjusted so that they are identical. Next proceed to degrade the rise time until nearly identical pulses are seen and then readjust the prf and proceed with the delay measurements.

* * * * * * *
* *
*

Pulse Superposition Method for Measuring Ultrasonic Wave Velocities in Solids

H. J. McSkimin
Bell Telephone Laboratories, Incorporated, Murray Hill, New Jersey

(Received September 6, 1960)

The frequently used pulse method of measuring ultrasonic wave velocities in solids involves a high-frequency quartz crystal transducer cemented to one end of a specimen having parallel end faces. The phase shift for waves reflected from the transducer must be considered for highest accuracy. It is shown that combining several measurements of phase delay (at two frequencies differing by approximately 10%) with a theoretical analysis of the reflection phase angle makes possible a determination of velocity to within one part in 5000 for round-trip delays greater than 5 μsec. Indirectly, the approximate thickness of the cement bond between transducer and specimen can be determined. The advantages of the method for making measurements as a function of temperature or pressure are discussed.

I. INTRODUCTION

THE measurement of elastic moduli of solids by ultrasonic means has by now become a well established technique.[1–3] For the commonly employed high-frequency pulse techniques the measurement of wave velocities is of primary concern since the measurement of a sufficient number of them, along with the density, allows a determination of the adiabatic moduli.[4]

The basic problem encountered is to obtain values of *plane wave* velocity in the presence of a number of effects such as produced by diffraction and coupling to the transducer. The latter, can cause appreciable error if not properly minimized or evaluated, particularly if the properties of the transducer-to-specimen bond change greatly with temperature or pressure as is usually the case. This problem has been considered by a number of investigators,[5,6] although frequently has not been given due attention. Phase comparison techniques which take account of coupling effects have also been described.[7,8]

It is the purpose of this paper to describe a fairly simple method of taking into account the transducer coupling effect when the specific arrangement used involves a quartz crystal cemented to one end of the specimen as is perhaps most frequently used. A description of the apparatus used will be given, and illustrative data for fused silica and germanium listed.

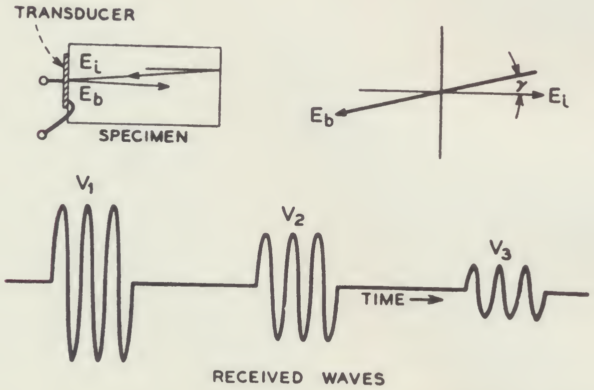


FIG. 1. Specimen with crystal transducer cemented to one end.

II. METHOD

2.1 Superposition Technique

Consider the transducer-specimen arrangement of Fig. 1. If a short duration rf pulse (train of waves) is initiated in the specimen, a series of echoes will result as shown by V_1, V_2, V_3, etc.

Assume now that identical pulse sequences are produced every T sec with T approximately equal to some multiple (p) of the round-trip delay in the specimen alone. For $p=2$ (Fig. 2) this will result in all the odd numbered echoes appearing in the same time slot, so that a display of the envelopes would appear as in Fig. 3. When T is critically adjusted, the amplitude of the summed echoes can be made a maximum. For this "in phase" condition, T measures the time between a crest (say) of V_1 and a crest of V_3. One cannot be certain which crests are involved at this point because of lack of resolution or distortion of the leading edges of pulses resulting from reflection within the transducer. In general terms, however, the following equation for T ("in phase" condition) can be written:

$$T=p\delta-(p\gamma/360f)+(n/f). \tag{2.1}$$

In the foregoing, δ is the round-trip delay which results from the specimen alone, γ is a phase angle associated with reflection of waves at the transducer (and including cement), f is the rf frequency in the pulse, p an integer previously defined, and n is an integer which can take on positive and negative values. The problem

[1] W. P. Mason, *Physical Acoustics and the Properties of Solids* (D. Van Nostrand Company, Inc., New York, 1958).
[2] H. B. Huntington, Solid State Physics **7**, 213 (1958).
[3] R. F. S. Hearmon, Phil. Mag. Supplement **5**, 323 (1956).
[4] See, for example, the description of E. W. Christoffel's results as listed in W. G. Cady, *Piezoelectricity* (McGraw-Hill Book Company, Inc., New York, 1946), p. 104.
[5] J. R. Neighbours, F. W. Bratten, and C. S. Smith, J. Appl. Phys. **23**, 389 (1952).
[6] S. Eros and J. R. Reitz, J. Appl. Phys. **29**, 683 (1958).
[7] H. J. McSkimin, IRE Trans. on Ultrasonic Eng. **UE 5**, 25 (1957).
[8] J. Williams and J. Lamb, J. Acoust. Soc. Am. **30**, 308 (1958).

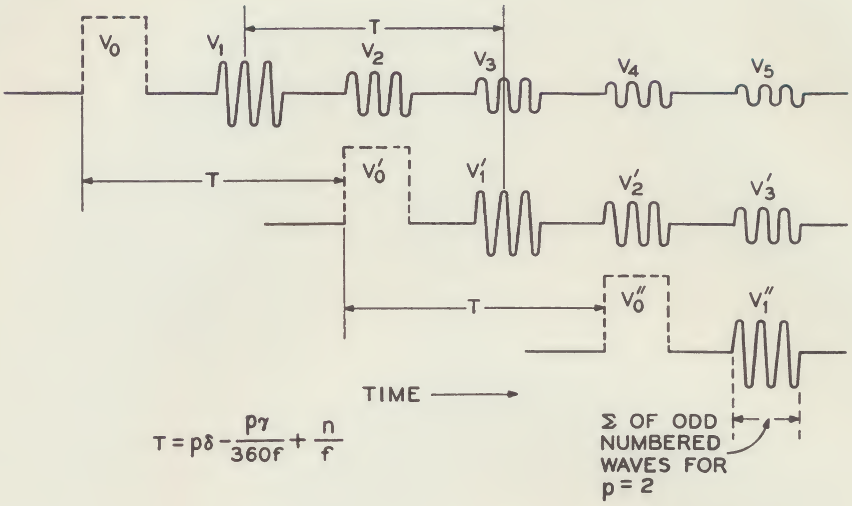


FIG. 2. Waves in specimen.

is to find the value of T corresponding to $n=0$, for then the delay time δ can be determined if the reflection phase angle at the transducer is known (i.e., if γ is known).

2.2 Theoretical Analysis for Phase Angle γ

If the mechanical properties of the materials comprising the composite structure (specimen, seal, transducer) are known, it is possible to calculate the reflection phase angle as shown by Fig. 4.[8,9] As an example, the angle γ for an X-cut quartz transducer, silicone oil, fused silica specimen combination is shown by Fig. 5 for two different seal thicknesses. Impedance values are:

$Z_s = 13.14\times 10^5$ mech ohms/cm² for fused silica specimen
$Z_1 = 1.37\times 10^5$ for the seal (DC 703 silicone oil)
$Z_2 = 15.3\times 10^5$ for X-cut quartz transducer.

2.3 Determining the Repetition Rate Frequency Corresponding to $n=0$

Note from Eq. (2.1) that the measured value T is somewhat a function of frequency f, particularly for large values of n. This fact may be used to good advantages as follows.

The change in T required to maintain exact phase addition of echoes as the wave frequency is changed from, say, f_H to f_L is from Eq. (2.1)

$$\Delta T = \frac{1}{f_L}\left(n - \frac{p\gamma_L}{360}\right) - \frac{1}{f_H}\left(n - \frac{p\gamma_H}{360}\right). \qquad (2.2)$$

Assuming that γ_H is to be evaluated at the resonance frequency of the quartz crystal, and that γ_L corresponds to a frequency 10% lower (i.e., $(f/f_r)=0.9$), phase angles can be computed for different values of seal thickness l_1 as shown in Table I.

For $n=0$, and values of γ_L and γ_H from Table I, ΔT may now be evaluated. Figure 6 shows a plot as a function of seal thickness measured in degrees (i.e., Bl), with $f_H = 20$ Mcs and $f_L = 18$ Mcs. Note that over a range of Bl from 0 to about 70°, $-\Delta T$ lies between 0.013 and 0.006 μsec for $p=2$. Thus, all experimentally determined values of T can be eliminated from con-

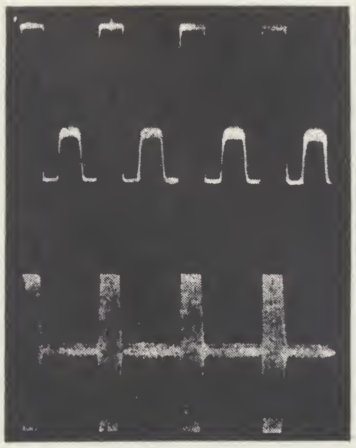


FIG. 3. Oscilloscope patterns for $p=2$. Top—envelopes showing received waves, bottom—applied rf pulses.

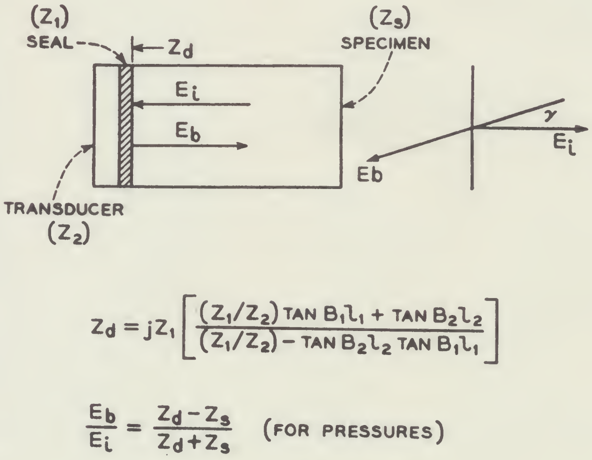
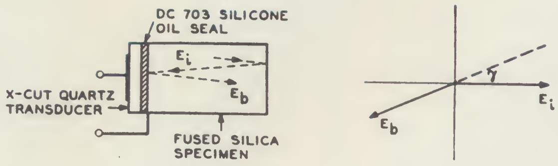


FIG. 4. Method of calculating γ.

[9] Refer to Appendix C of work cited in footnote 7.



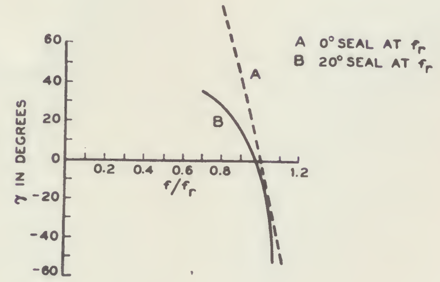


FIG. 5. γ versus frequency.

sideration except those for which ΔT lies within these limits.

For many combinations of impedances only one measured value of ΔT will be within limits, however, for relatively low specimen impedances two choices may exist. In this case, data for $p=3$ may readily be taken and compared with that for $p=2$. Equation (2.1), rewritten in explicit form for T/p, becomes

$$T/p=\delta+(1/f)[(n/p)-(\gamma/360)]. \qquad (2.3)$$

It is seen that T/p is a function of n/p, so that identical values of T/p will not appear in the experimental data for both $p=2$ and $p=3$ unless n is an even integer for $p=2$. Thus, the correct value of T/p (corresponding to $n=0$) can be chosen. This point will be illustrated in a following section. Note that the comparison of experimental data with the calculated results shown by Fig. 6 gives at least an approximate value for the seal thickness. Knowing this one can calculate the value of γ to be used in Eq. (2.3). From the curves of Fig. 5, the

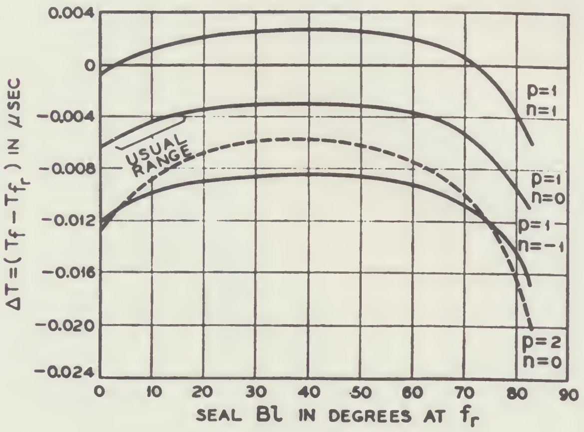


FIG. 6. ΔT versus seal thickness.

advantage of using a wave frequency near the resonance of the transducer is seen. For thin seals γ is quite small and may be negligible. Furthermore, if the frequency is continually adjusted, for example over a temperature run, to approximately equal the known resonance frequency of the transducer, γ will remain essentially constant so that even large variations of seal properties will not affect the ratio δ/δ_0, where δ_0 is the previously measured delay at room temperature.

The case for $p=1$ will now be considered. Obviously the applied pulses will obscure the echoes if the sequence is unbroken. However, what can be done is to continue the sequence long enough to establish a stable pattern and then drop off one or more of the applied pulses. During this period the desired echoes from all previously applied pulses will appear and can be critically phase added (see Fig. 7).

From Fig. 6 it can be seen that the ΔT values corresponding to $n=0$ are one-half those for $p=2$ so that the ambiguity mentioned in the foregoing is removed. Furthermore, since all of the echoes are used (instead of every other one) measurements can be made on materials having greater attenuation. These advantages make it worthwhile to set up the somewhat more complicated circuits involved.

III. EQUIPMENT USED

3.1 Repetition Rate Oscillator

A stable L-C oscillator (General Radio 1330A) covering the frequency range used (15–400 kc) was available. The short time drift was less than one part in 100 000.

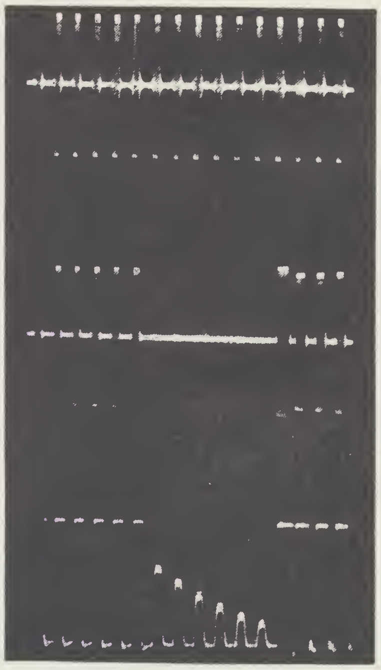


FIG. 7. Oscilloscope patterns for $p=1$. Top—repeated rf pulses, middle—applied rf pulses, bottom—envelopes showing received waves.

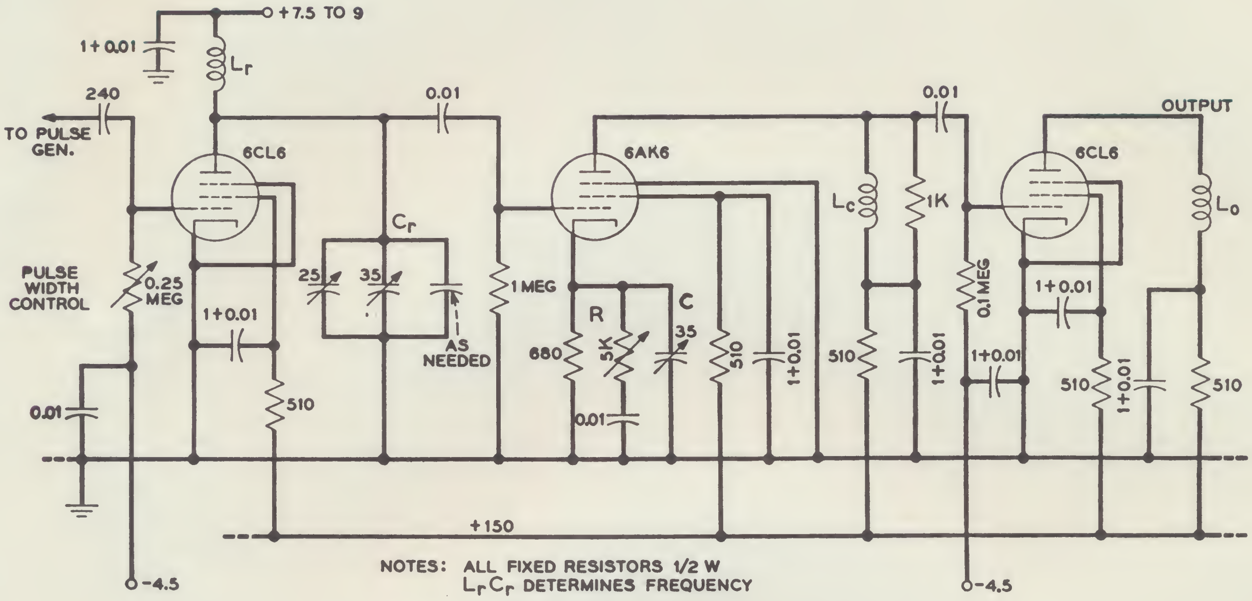


FIG. 8. rf pulse generator.

3.2 Gas Tube Pulse Generator

The output of the above oscillator was squared by a simple hard tube circuit to increase the rise rate. The positive swing fired a Chatham Electronics 1258 gas thyratron, giving a negative pulse of about 150 v with repetition rates to about 400 kc.

3.3 Ringing Circuit

The L-C ringing circuit as shown by Fig. 8 was actuated by the output pulse of the gas tube, current flowing in the anode circuit of the 6CL6 being suddenly interrupted. Quenching after several microseconds was obtained when conduction in the 6CL6 was restored. With a pentode used in the way shown, leakage of the keying pulse is prevented. Another feature of interest is the use of the 6AK6 buffer amplifier in providing the necessary negative resistance to prevent decay of oscillations over the pulse width. *R* and *C* are adjusted for this purpose. (Values shown are for operation around 20 Mcs.)

The frequency of the rf pulse can be measured to within one part in 1000 by beating the output against cw from a standard signal generator.

TABLE I. Calculated values of phase angle γ.[a]

$f/f_r=0.9$ B_1l_1 (degrees)	γ_L (degrees)	$f/f_r=1$ B_1l_1 (degrees)	γ_H (degrees)
0	41.2	0	0
10	24.7	11.1	−2.33
20	18	22.2	−4.90
45	6.77	50.0	−14.17
60	3.10	66.7	−27.4
75	0	83.3	−83.3

[a] $B_1=2\pi f/\text{velocity}$.

3.4 Frequency Measurement

A Hewlett Packard model 524B counter was used for determining the frequency of the repetition rate oscillator.

3.5 Amplifier—Detector—Scope

Two amplifiers were available for the present study, of about 75 db gain, centered at 10 and 20 Mcs and with a 5-Mcs pass band. The usual diode detector and limiter were used, with a Tektronix 535A oscilloscope for video visualization of pulse patterns.

3.6 Temperature Control

The specimens under test were temperature controlled to within 0.2° by means of a Precision Scientific Company water circulator.

3.7 Over-All Circuit

Figure 9 shows a block diagram of the equipment used.

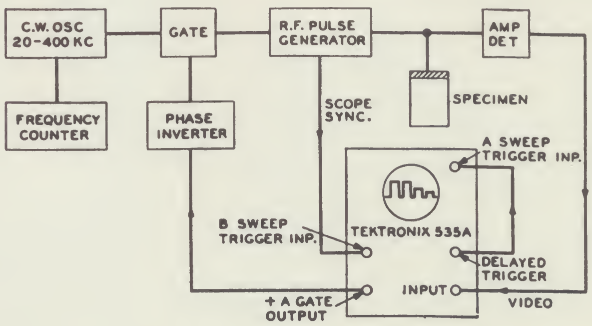


FIG. 9. Block diagram of apparatus.

TABLE II. Delay time measurements for longitudinal waves in germanium.[a]

	$p=2$			$p=3$	
n	$T/2$ in μs	ΔT in μs	n	$T/3$ in μs	ΔT in μs
−2	8.9458	−0.0163	−1	8.9789	−0.0131
−1	8.9706	−0.0103	0	*8.9956*	−0.0073
0	*8.9956*	−0.0048	+1	9.0122	−0.0022
+1	9.0206	+0.0003	+2	9.0290	−0.0029
+2	9.0455	+0.0056	+3	9.0454	+0.0088
+3	9.0706	+0.0109	+4	9.0621	+0.0141

[a] (1) Propagation along [100], $l=0.8701$ in. diam $=\sim 0.75$ in. (2) $\Delta T = T_{18\text{ Mcs}} - T_{20\text{ Mcs}}$. (3) Temperature = 25.0°C. (4) Velocity $=4.914\times 10^5$ cm/sec.

IV. EXPERIMENTAL RESULTS

In all, four specimens were tested, one of germanium, three of fused silica. Velocities were calculated, based on measured thickness. For the fused silica specimens, predicted free-space velocities (measured by a phase comparison technique involving the use of a buffer rod[7]) were available for direct comparison.

Table II shows data obtained for a germanium crystal, longitudinal waves being propagated by a 20-Mcs X-cut quartz transducer cemented with a very thin film of viscous polystyrene fluid (impedance approximately the same as for silicone oil). The value for velocity obtained agrees well with other data available.[10]

TABLE III. Delay time measurements for longitudinal waves in fused silica block.[a]

	$p=2$			$p=3$	
n	$T/2$ in μs	ΔT in μs	n	$T/3$ in μs	ΔT in μs
+3	7.0768	+0.0051	+4	7.0678	+0.0072
+2	7.0516	0	+3	7.0515	+0.0005
+1	7.0268	−0.0059	+2	7.0350	−0.0054
0	*7.0013*	−0.0105	+1	7.0186	−0.0119
−1	6.9761	−0.0151	0	*7.0015*	−0.0158

[a] (1) Specimen dimensions: 6 in. $\times 2\frac{9}{16}$ in. $\times 0.8198$ in. (2) $\Delta T = T_{18\text{ Mcs}} - T_{20\text{ Mcs}}$. (3) Temperature = 25.0°C. (4) Velocity $=5.948\times 10^5$ cm/sec.

[10] H. J. McSkimin, J. Appl. Phys. 24, 988 (1953).

The longitudinal wave velocity in a precision-ground block of fused silica was also measured. Data were obtained at both 10 and 20 Mcs. (See Table III for 20 Mcs data.) On account of the lower mechanical impedance (compared to germanium) the $p=2$ data limits the $n=0$ delay time to two choices instead of only one. One ($n=1$) can be excluded by comparing data for $p=2$ and $p=3$ (i.e., n is odd). Hence, only one possible value is left. Phase velocity measurements were also made for this specimen. The two independently obtained values agreed to within one part in 5000.

The circuit of Fig. 9 was used with the phase inverter and gate omitted.

Data were also obtained for a fused silica specimen using the full complement of equipment shown in Fig. 9.

TABLE IV. Delay time measurements for longitudinal waves in fused silica specimen ($p=1$).[a]

n	T in μs	ΔT in μs
+2	6.4779	+0.0074
+1	6.4282	+0.0017
0	*6.3783*	−0.0042
−1	6.3284	−0.0102

[a] (1) $\Delta T = T_{18\text{ Mcs}} - T_{20\text{ Mcs}}$. (2) Calculated limits for ΔT are −0.003 to −0.0064 μs. (3) Specimen dimensions: 0.7506″ × 0.55″ diam. (4) Temperature = 27.4°C. (5) Velocity $=5.978\times 10^5$ cm/sec.

The "A" sweep generator of the Tektronix 535A oscilloscope was used to turn off the gate at a submultiple of the repetition rate of the rf pulses.

Table IV lists the data obtained. Note that from Fig. 6 ($p=1$) there is only one value of ΔT which lies within the appropriate range; hence, there is no ambiguity of results. Comparison of results with phase comparison measurements on the same sample again indicated agreement to within one part in 5000.

ACKNOWLEDGMENT

Appreciation is expressed to T. B. Bateman for helpful suggestions regarding circuits and for making several of the measurements reported in this paper.